

Curved CO₂ laser waveguides for neurosurgery

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N00014-90-C-0028

ABSTRACT

We have developed a method of fabricating permanently curved hollow metallic waveguides of both constant and tapered inside diameter. This method is based on the use of soluble glass mandrels. In tests with laboratory CO₂ lasers we have shown that even without interior dielectric layers these devices can exhibit low loss; e.g., a 22 cm long, 2mm ID guide with a 65° exterior bend transmits more than 90% of properly launched input radiation. We discuss methods of cooling these devices and requirements for their use in neurosurgery.

2. INTRODUCTION

Since its invention twenty five years ago, the CO₂ laser has become the workhorse of surgical lasers. Some reasons for its popularity in surgery in general and neurosurgery in particular are the following: it is hemostatic; it is very precise, capable of incising or vaporizing selected tissue with minimal damage to adjacent areas; it can produce power sufficient for surgery; it is capable of continuous-wave or pulsed operation; and it can be more gentle than conventional methods of tissue removal.

Any surgical laser must be equipped with a delivery system capable of accurately and conveniently directing its beam. The devices which have made precise CO₂ laser surgery a reality are the articulated arm and the operating microscope. The articulated arm is a precisely counterbalanced system of pivoting mirrors connected by tubes. The proximal end of the arm is connected to the laser and the distal end to the operating microscope or a handpiece. However the articulated arm/operating microscope system is large and cumbersome, and the need for smaller, more flexible replacements or additions has long been recognized. The technologies most often considered for alternative delivery systems are polycrystalline fibers and hollow waveguides¹. Straight hollow ceramic waveguides of small interior diameter have been developed for use in surgical procedures^{2,3}. In this paper we discuss the development of curved hollow metallic waveguides intended

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specifically for use as handpieces in neurosurgery. These handpieces are intended to function initially as complements to articulated arm delivery systems.

We believe that if a handpiece is to be useful in laser neurosurgery it must: (1) be bent or offset to allow line-of-sight vision unblocked by the surgeon's hand, (2) be as slender as possible, (3) be rugged enough to survive the rigors of the operating room environment, (4) resist damage from smoke, fluids, etc. that accompany laser surgery, (5) be insensitive to the input beam displacement caused by the motion of even well-aligned articulated arms, (6) transmit the visible helium-neon laser beam used to locate the invisible CO₂ laser beam, (7) deliver a beam with low divergence, (8) remain sufficiently cool that it does not cause either inadvertent damage to tissue or discomfort to the surgeon holding it, (9) deliver the beam with relatively low loss, and (10) lend itself to relatively low-cost manufacture. We believe that meeting requirements (4) and (8) can be particularly difficult in neurosurgery. Hollow waveguides are commonly cooled with gas flowed through their bores. This gas flow also prevents potentially damaging material from entering the tube. Flowing gas onto the brain is, however, unacceptable. On the other hand, we believe that requirement (9) is somewhat less strict in neurosurgery, where laser power requirements can be relatively low.

3. FABRICATION

Substantial effort has been directed toward the development of small-diameter hollow metallic waveguides. However the majority of published work is theoretical. Fabrication of these devices has proven a formidable task. Three general fabrication methods have been described. Perhaps the earliest involves the use of a gold-containing screen ink which is coated onto the inner surface of a quartz tube and fired^{4,5}. The limitations of this method are apparent. More recently, methods have been developed in which optical coatings are chemically⁶ or electrochemically⁷ deposited onto the inner surfaces of tubes having excellent inside surface finish. The third approach involves the use of a tubular mandrel of excellent outside surface quality which is first optically coated, then electroplated with a thick layer of a structural material (most often nickel), and finally dissolved. Materials reported to have been used for mandrels include aluminum and plastic^{8,9}. We believe the latter method to be the most versatile, but consider aluminum and plastic to be less than ideal mandrel materials. Small diameter aluminum tubes of excellent surface finish are difficult to obtain and are easily bent, scratched, etc. Small diameter plastic tubes flex easily, and optically coating many plastics can be a difficult task. Neither material is easily formed into complex shapes. We decided therefore to investigate the use of glass as a mandrel material.

We initially considered the use of water soluble glasses. Although many such materials are known¹⁰, we were unable to find one well suited to our purpose. Some, such as zinc chloride are too hygroscopic. Others, such as sodium silicate and many borate glasses dissolve only

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slowly in water. Most, including sodium phosphate, have high thermal expansion coefficients and are difficult to work with. We therefore settled on borosilicate glass¹¹, which we dissolve with hydrofluoric acid. Borosilicate glass is easily obtained in a wide variety of sizes, has excellent surface finish without polishing, is rigid, is easily formed into desired shapes, and withstands the harsh conditions under which optical coatings are applied. Although hydrofluoric acid is dangerous to humans, it is not an oxidizing acid and is benign toward many common metals and materials.

We fabricate waveguides using the following procedure. Glass tubes are first formed into desired shapes and then optically coated in vacuum. (Although we have developed a method of applying dielectric coatings¹², all waveguides discussed here have interior surfaces of either copper, silver, or gold.) A structural layer of nickel is electroformed onto the coated mandrel, and the glass is subsequently dissolved. Examples of waveguides fabricated by this process shown in Figs. 1 and 2.



Fig. 1. Curved hollow waveguides of constant internal diameter.



Fig. 2. Curved and tapered guides.

All waveguides shown in Figs. 1 and 2 have interior surfaces of gold. The inside diameter of the waveguides in Fig. 1 is 2mm. We have fabricated similar devices ranging in inside diameter from several hundred microns to seven millimeters.

4. EVALUATION

We discuss the performance of the waveguides in terms of the criteria presented in the introduction. It is clear that the waveguides shown in Figs. 1 and 2 have sufficient curvature to allow line-of-sight vision around them. We believe they have diameters small enough to make them useful in neurosurgery. Waveguides of wall thickness greater than a few hundredths of an inch are structurally robust. We have not yet thoroughly investigated the effects material ejected during cutting on

the waveguides or the sensitivity of these devices to beam displacement caused by motion of the articulated arm. However straight hollow waveguides of smaller inside diameter have been used successfully with articulated arm delivery systems³. All waveguides shown transmit the 633 nm helium-neon laser beam. Transmission properties are functions of the shape of the waveguide and the input beam launch conditions. As an example of the loss achievable, the waveguide on the lower right of Fig. 1 can transmit as much as 92% of input gaussian-mode CO₂ laser radiation. In order to minimize loss, a polarized beam must be launched such that it propagates in a so-called whispering-gallery mode, in which it interacts primarily with the outer wall of the guide. (For minimum loss the beam was launched into the less-curved end of the guide.) Output beam divergence is also dependent upon launch conditions. Modes propagating in the whispering-gallery have elliptical profiles. The divergence characteristics of these beams have been discussed previously¹³. It is also possible to launch beams that emerge in approximately circular patterns. Preliminary experiments show these beams to have somewhat higher divergence than whispering-gallery modes. They may be composed of non-whispering-gallery modes and/or multiple whispering gallery modes having higher divergence than the lowest order mode. As expected, beam divergence tends to be greater for the tapered waveguides than for the non-tapered guides. If not actively cooled, all waveguides shown in Figs. 1 and 2 exhibit unacceptable temperature rise. In order to solve this problem we have electroformed small cooling channels to the exterior surface of a waveguide and passed air (provided by a pump supplied within the laser cabinet) through these channels. Preliminary experiments indicate that this method will allow at least 10 watts and possibly considerably more power to be dissipated within the waveguide without appreciable temperature rise or the necessity to force air out the distal end of the waveguide.

5. CONCLUSION

We have developed a method of fabricating curved and/ or tapered hollow metallic waveguides. We believe that these waveguides have shapes and transmission characteristics well suited to neurosurgery and that the fabrication procedure is simple enough to allow them to be fabricated at reasonable cost.

6. ACKNOWLEDGEMENTS

This work was partially supported by the Medical Free Electron Laser Program through contract N-00014-90-C0028 and by the Washington Square Foundation Project #143. The help of Dr. F. Tang in performing loss measurements is gratefully acknowledged.

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